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APPLICATION

FOR

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TITLE: REDUCING CHROMATIC ABERRATION IN IMAGES FORMED BY EMISSION ELECTRONS

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REDUCING CHROMATIC ABERRATION IN IMAGES FORMED BY EMISSION ELECTRONS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority from U.S. provisional patent application Serial No. 60/393,133 which is entitled "Low Voltage Time of Flight Electron Emission Microscope," filed July 3, 2002, and is hereby incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present invention relates to imaging objects with emission electrons.

BACKGROUND OF THE INVENTION

[0003] Many modern electrical imaging devices, such as modern electron emission mic roscopes (EEMs), image an object of interest (also called specimen or sample) by first accelerating and focusing electrons emitted from the object using an electric/magnetic objective lens, and then further magnifying the image by using a series of electric/magnetic projector lenses. An electric/magnetic lens typically generates electric or magnetic fields, or a mix of both, in the path of a beam of emitted electrons for altering the trajectories of the emitted electrons, analogous to the way a glass lens alters the trajectory of a beam of light.

[0004] A typical conventional EEM has a radiation source for illuminating an object to be imaged, an electron detector for detecting electrons emitted from the object as a result of the radiation, and one or more electric/magnetic lenses for directing the emitted electrons towards the electron detector to form a magnified image of the object at the detector. In a typical EEM, an electrostatic objective

lens is positioned close to the object and has an electrical potential higher than that of the object (usually in the range of 10 to 15 kV) for extracting and accelerating the emitted electrons.

[0005] The focal length of such an electric/magnetic lens varies with the kinetic energy of the electrons focused by it. That is, electrons of different energies will be focused at different focal points. For example, the focal length of a magnetic lens for an electron beam of kinetic energy E may be approximated by

$$\frac{1}{f} = \frac{1}{8mE}\int_{z_1}^{z_2} B_z^2 \, dz \,, \qquad (1)$$

where m is the electron mass, and B_z is the axial magnetic field distribution. As such, a beam of electrons with dispersed energies is not focused in a single plane by an electric/magnetic lens. Not focusing a beam in a single plane results in distortion of the image formed on a single plane. This distortion due to variation in kinetic energy of the emitted electrons is referred to as chromatic aberration. Thus, the spatial resolution of electric/magnetic lenses is limited in part by chromatic aberration.

[0006] In EEM, the initial kinetic energies of secondary electrons excited by X-ray radiation typically range from several to tens of electron-volts, and, consequently, chromatic aberration limits spatial resolution of an X-ray photoelectron emission microscope (XPEEM) to about 100 nm.

[0007] Several techniques have been developed for reducing chromatic aberration in EEM. The general approach is to filter out emitted electrons having kinetic energies outside a certain range. For example, contrast apertures and Wien filters have been used for such a purpose, improving spatial resolution of XPEEMs to about 20 nm. However, when emitted electrons of varied energies are eliminated, the intensity of emitted electrons arriving at the detector is reduced. Further, certain information is lost. Particularly, a full emission spectrum cannot be obtained.

[0008] An alternative approach is to operate an EEM in a time of flight (TOF) mode as, for example, described in "Time-of-Flight Photoelectron Emission Microscopy TOF-PEEM: first results", *Nuclear Instruments And Methods in Physics Research*, A 406, (1998), 499-506, H. Spiecker *et al*, ("Spiecker"). Spiecker discloses a photoelectron emission microscope (PEEM) with a pulsed radiation source. Emitted electrons are dispersed in a drift tube downstream of the imaging optics. The electrons are retarded at the entrance of the drift tube from ~700 eV to a drift energy of less than 100 eV and are imaged on a multi-channel plate (MCP) at the end of the tube. The electrons are then accelerated to a scintillator screen having a short decay time. Emitted electrons produced from a single radiation pulse are spatially separated in the drift tube due to the spread in their kinetic energy as the drift time of each electron is dependent on its drift energy. The images formed by electrons in different energy ranges are separately recorded in time. The chromatic aberration in each single image is reduced because the energy spread in electrons forming a single image is smaller than the spread in all transmitted electrons. However, this approach has several limitations. Specifically, only electrons within a narrow energy range are collected for each image and they represent only a small fraction of all of the emitted electrons. Accordingly, the acquisition time for a single image is long. As the TOF spectrometer is placed after the imaging optics, initial electron angular motions tend to limit separation of electrons with different energies within the drift tube, and hence the final spatial resolution of the image. Further, it is difficult to integrate this type of TOF spectrometer into a conventional XPEEM.

[0009] Another approach is to use a tetrode mirror for correcting both chromatic and spherical aberration, as described in "SMART electron optics", in *12th European Congress on Electron Microscopy, Proceedings Volume III*, Instrumentation and Methodology, (2000), 81-4, D. Preikszas *et al.* The spatial resolution can be improved to about 2 nm with this approach. However, this approach requires complicated, precise design and positioning of the various lenses and, particularly, the tetrode mirror.

[0010] Thus, there is a need for an improved imaging device using emitted electrons with low chromatic aberration wherein both high spatial resolution and full spectrum of emitted electrons can be obtained simultaneously.

SUMMARY OF THE INVENTION

[0011] In accordance with an aspect of the present invention, an imaging device, such as an EEM, includes an electric/magnetic lens is used to focus pulsed electrons emitted from an object on to a target plane. Before a pulse of emitted electrons reaches the lens, electrons are spatially separated in dependence on their respective kinetic energies and are then subject to a time varying electric field. The electric field compensates for variations in kinetic energies, thus causing the electrons to be focused proximate a single plane, reducing chromatic aberration. The varying electric field may be provided by varying an electric potential at the lens, such as by varying a voltage supplied to an electrode at the lens. This potential effectively varies the focal length of the lens in time, in order to compensate for variations in kinetic energies of electrons arriving at the lens.

[0012] A drift chamber may optionally be provided for better spatial separation. As can be appreciated, since the energy spread in the emitted electrons is reduced at the lens, distortions in the image formed at the target plane due to chromatic aberration are reduced. The kinetic energy of the pulsed emitted beam of electrons may be kept relatively low, e.g. between 20 to 100 eV, so that they have significantly different arrival times at the lens. A low aberration electric/magnetic objective lens may be provided to reduce the effect of the initial angular spread of the emitted electrons. The magnetic and electric field strengths rapidly decrease from the specimen surface so as to strongly collimate the emitted electrons, thus reducing on-axis lens aberrations and minimising the effect of initial angular distribution on their transit times.

[0013] In accordance with an aspect of the invention, there is provided a

method of imaging an object, includes illuminating the object to emit at least one pulse of electrons; directing the pulse of electrons along an optical path through a lens, towards a target to form an image of the object at the target; spatially separating electrons within the pulse in dependence on their kinetic energies, before the electrons reach the lens; providing a time varying electric field along the optical path remote from the object, the field varying in time so that the amount of energy provided to individual ones of the electrons in the pulse depends on their spatial separation within the pulse, thereby reducing energy dispersion of electrons passing through the lens and reducing the chromatic aberration in the image.

[0014] In accordance with another aspect of the invention there is provided an apparatus for imaging an object, includes a lens for focusing pulsed electrons emitted from the object and directed along an optical axis to form an image of the object at a target, and a correcting element positioned remote from the object, the correcting element electrically biased to have a dynamically changing voltage for correcting the kinetic energies of electrons passing through the lens, the voltage variable in synchronization with the pulsed electrons for correcting the kinetic energies of the pulsed electrons in dependence on arrival times at the correcting element.

[0015] In accordance with yet another aspect of the invention there is provided a method of imaging an object. The method includes illuminating the object to emit at least one pulse of electrons; directing the pulse of electrons along an optical path through a lens, towards a target to form an image of the object at the target; spatially separating electrons within the pulse in dependence on their kinetic energies, before the electrons reach the lens; varying a focal strength of the lens in time to compensate for variations in kinetic energies of individual ones of the electrons in the pulse, thereby reducing the chromatic aberration in the image.

[0016] In accordance with still another aspect of the invention there is

provided an electric/magnetic lens for use in an electron emission microscope. The lens includes an electrode, having a controllable potential for varying energy imparted to electrons arriving at the electrode, and thereby the focal length of the lens.

[0017] Other aspects, features and advantages of the invention will become apparent to those of ordinary skill in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] In the figures, which illustrate exemplary embodiments of the invention,

[0019] **FIG. 1** is a simplified schematic diagram illustrating an EEM exemplary of an embodiment of the present invention;

[0020] **FIG. 2** is a simplified schematic diagram illustrating an EEM exemplary of a further embodiment of the present invention;

[0021] **FIG. 3** is a schematic section view of the objective lens shown in **FIGS. 1** and **2**; and

[0022] **FIG. 4** is a line graph illustrating an example time varying voltage applied to an electrode of the EEM of **FIGS. 1** or **2**, in manners exemplary of an embodiment of the present invention.

DETAILED DESCRIPTION

[0023] **FIG. 1** illustrates an EEM **10,** exemplary of an embodiment of the present invention. EEM **10** includes an objective lens **26**, a drift chamber **28,** a dynamic projector lens **12**, and an electron detector **34**. An optional

deflector/stigmator unit **32** also forms part of EEM **10**. EEM **10** may be used to image an object **16** or a portion thereof using pulsed electrons emitted from object **16**. Beam **38** may be a beam of electromagnetic waves, such as UV light or X-rays, or charged particles, such as electrons. A radiation source (not shown) may form part of EEM **10** to excite object **16** to emit electrons by generating radiation beam **38**. Drift chamber **28** may have an axial length between 20 and 100 cm. An example detector **34** may include a multi-channel-plate (MCP) and a digital sampling oscilloscope to image object **16**.

[0024] Lens **12** is positioned at a distance from object **16** to focus electrons emitted from object **16** in a target plane **18** along an optical axis **20** to form an image **22** of object **16**.

[0025] An electrode **14** controls the electrical potential at lens **12**, and thereby the electric field along optical axis **20** between drift chamber **28** and lens **12**. The voltage on electrode **14** may be supplied by a signal generator and thus varied in time and synchronized with an input signal. Electrode **14** may take various shapes and be placed at various locations along optical axis **20**. In EEM **10**, exemplary projector lens **12** is a weak focusing electrostatic lens and electrode **14** is incorporated in projector lens **12**: electrode **14** of projector lens **12** is biased by a signal generator for controlling the electrical potential at lens **12**. Electrical potential at lens **12** can also be varied in various other manners known to a person skilled in the art.

[0026] Viewed another way, the potential at electrode **14** varies the focal length of lens **12**, and allows the focal length of lens **12** to vary in time so as to compensate for the spread in kinetic energies of the emitted electrons focused by lens **12**.

[0027] Electrode **14** varies potential at lens **12**, and thereby the field along axis **20**, compensating for the chromatic aberration effect in manners exemplary of the present invention, as described herein.

[0028] Specifically, the kinetic energy of an emitted electron arriving at lens **12** depends on both its initial kinetic energy at object **16** and the electrical potential at lens **12** at the time of arrival. Electrons within a pulse of electrons emitted from object **16** will arrive at lens **12** at different times if they have different initial kinetic energies. That is, the electrons will be spatially separated as a result of their travel along optical axis **20**. Thus, when the potential at lens **12** varies as emitted electrons arrive, the kinetic energies of the emitted electrons passing lens **12** are modulated by the variance of the potential and will vary depending on their arrival time at lens **12**. With a beam of pulsed electrons emitted from object **16**, the potential at lens **12** can be controlled to vary in time to reduce the kinetic energy dispersion of electrons passing through lens **12**. As the energy dispersion in the electrons at the lens is reduced, chromatic aberration can be reduced.

[0029] Again, viewed another way, the focal length of lens **12** varies in dependence on the potential at electrode **14**. Change in focal length of lens **12** with time cause electrons with different arrival energies to be focused in the same plane.

[0030] The potential change required at lens **12** can be estimated as follows. Assuming an infinitely short pulse width, and denoting the spread in initial kinetic energy as $?E_i$, the spread in arrival time at projector lens **12** as $?t$, the required change in potential, $?V(t)$, within time $?t$ for eliminating any energy spread at lens **12** is, in theory,

$$?V(t) = ?E_i/e. \qquad (2)$$

[0031] Beside the spread in initial kinetic energy, there are two additional factors that affect the spread in arrival time at lens **12**: the speeds at which the pulsed electrons travel and the traveling distance between object **16** and lens **12**. Clearly lower speeds and longer distance will result in a larger spread in arrival time.

[0032] In order to sufficiently spatially separate electrons of different initial

energies in a pulse of emitted electrons, the pulsed electrons are allowed to travel a sufficient distance before they reach lens **12**. Drift chamber **28** may therefore be provided. Drift chamber **28** electrically shields pulsed electrons passing through it from external electrical and magnetic fields. Drift chamber **28** may be biased to a low potential so that pulsed electrons entering it will have low kinetic energies and travel at low speeds within it.

[0033] Further, the kinetic energies of the pulsed electrons may be kept low before they reach lens **12** so that they travel at low speeds.

[0034] Optionally, projector lens **12** of EEM **10** may be replaced with a magnetic projector lens **12'** as in EEM **10'** depicted in **FIG. 2**. In the case of a magnetic lens, an electrically biased grid, acting as an electrode **14**, may be placed between the pole-pieces of the magnetic lens to vary the potential at lens **12'**.

[0035] An additional objective lens **26** (**FIGS. 1 and 2**) forms part of EEM **10** and **10'** and is designed to work with a time of flight spectrometer, but may be designed to also work with other types of imaging energy filters, such as a Wien filter or an Omega filter. The optical magnification of objective lens **26** may be as high as 500 to 10,000. Objective lens **26** may have a focal length ranging from 20 to 200 μm. Objective lens **26** may use mixed electric and magnetic fields to extract and guide electrons emitted from object **16**.

[0036] An exemplary embodiment of objective lens **26** is more particularly illustrated in **FIG. 3**. As illustrated, objective lens **26** may have a tapered tip **40** which has a small opening **42**. The diameter of opening **42** of tapered tip **40** may be made small so that both axial magnetic and electric fields fall off sharply at opening **42**. For example, diameters between 50 to 200 μm may be used. A smaller opening **42** results in smaller chromatic and spherical on-axis aberration coefficients. Magnetic fields are generated by electromagnet **44** placed below object **16**. Electromagnet **44** comprises an iron casing **46** enclosing a coil **48**. Casing **46** has a central opening **50** in its top plate for producing magnetic fields

in the area around opening **42** of objective lens **26**. Object **16** may also be placed in opening **42** of the top plate.

[0037] Of course, other types of objective lenses, such as those used in conventional EEMs may also be used. For example, objective lens **26** may be replaced with an electrostatic objective lens.

[0038] In operation, a radiation source radiates object **16** placed close to objective lens **26** with radiation beam **38**, as illustrated in **FIG. 1** and **2**. To generate pulsed emission electrons, radiation beam **38** may be pulsed. Pulses of electrons that have short width and are well separated are preferable because of easy separation of the electrons. Calculations show that beams with pulse width around one nanosecond for overall transit time of over 100 ns, will produce good results. In general, the width of the pulse at the specimen should be limited to be a small fraction of the total transit time. Of course, as can be appreciated, practical pulse width and repetition time are limited by many factors including the time resolution of various elements and control components of the microscope and efficiency considerations. For example, a pulse width of about 10 ns may be appropriate for longer overall transit times.

[0039] Alternatively, radiation beam **38** may be continuous or have a wide pulse width, in which case, object **16** may be driven by nanosecond-wide low voltage pulses at a desired repetition rate which effectively block emission of electrons.

[0040] Pulsed electrons emitted from object **16** may include secondary electrons, photoelectrons or other types of electrons, depending on the characteristics of radiation beam **38** and object **16**.

[0041] Object **16** may be received in proximity to optional objective lens **26**. Lens **26** may be electrically biased relative to object **16**. Pulsed electrons emitted from object **16** are thus extracted and accelerated by objective lens **26** towards detector **34**. A low potential difference between object **16** and object

lens **26** may be advantageous to keep the kinetic energies of the pulsed electrons low. Thus, for example, object **16** may be biased to a voltage ranging from –100 to –20 volts, while the electrodes of objective lens **26** are grounded. Where the potential difference between object **16** and objective lens **26** is low, it may be advantageous to use an objective lens **26** as illustrated in **FIG. 3**. To operate such an objective lens **26**, an electrical current is run through coil **48** to energize electromagnet **44** and thus generate the desired magnetic fields in objective lens **26**. The magnetic flux flows around within iron casing **46** and through opening **50** to tapered tip **40**.

[0042] Advantageously, the magnetic fields help collimate the emitted electrons, reducing the dependence of their subsequent transit times less on their initial angle of emission. Conveniently, a mixed field objective lens may give significantly lower on-axis chromatic and spherical aberrations in the final image than a purely electrostatic or purely magnetic field objective lens.

[0043] After exiting objective lens **26**, pulsed electrons that are not blocked by deflector/stigmator unit **32** enter drift chamber **28**. Drift chamber **28** may also be electrically biased with reference to object **16** so that there is a low potential difference between drift chamber **28** and object **16**, which can be, for example between 10 and 100 V.

[0044] Since the potential difference between object **16** and drift chamber **28** is low, pulsed electrons entering drift chamber **28** will have low kinetic energies. Consequently, pulsed electrons travel at low speeds within drift chamber **28**. Because the pulses are well separated from each other and electrons having different kinetic energies travel at different speeds, a pulse of pulsed electrons drifting in drift chamber **28** gradually become spatially separated along optical axis **20**. Faster electrons will exit drift chamber **28** earlier and slower electrons will exit later. Workable time separation for a single pulse can vary from several to tens of nanoseconds in a typical configuration.

[0045] After exiting drift chamber **28**, pulsed electrons will gain or lose kinetic

energy depending on the electric field along optical axis **20**, as influenced by the electrical potential difference between drift chamber **28** and projector lens **12** (or **12'**). If drift chamber **28** has a higher potential than that at lens **12**(or **12'**), pulsed electrons will lose kinetic energy. If drift chamber **28** has a lower potential, pulsed electrons will gain kinetic energy. The larger the difference, the larger the change in kinetic energy.

[0046] In any event, electrons eventually arrive at projector lens **12** (or **12'**). Electrode **14** modulates potential at lens **12** (or **12'**) by several volts within a few nanoseconds using existing technology. As the voltage changes over time, the arriving pulsed electrons will gain or lose energy differently depending on when they reach projector lens **12** or **12'**, effectively varying the focal length of projector lens **12**. For example, if the potential at lens **12** (or **12'**) is higher than at drift chamber **28** and increases over time, those pulsed electrons reaching projector lens **12** (or **12'**) earlier will gain less kinetic energies than those reaching there later. As those that arrive earlier have higher initial kinetic energies, the spread in kinetic energy is reduced. Thus, it is possible to modulate the voltage on the electrodes of lens **12**, to compensate for the spread in kinetic energies of the pulsed electrons at projector lens **12** so that the effect of chromatic aberration in the formed image of object **16** can be reduced.

[0047] For example, the signal generator of electrode **14** can be synchronized with the radiation pulse **38**. Each radiation pulse **38** triggers a cycle of voltage change on electrode **14**. In each cycle, the voltage may be varied to minimize the energy spread in the electrons of a pulse traveling through projector lens **12**.

[0048] As will be appreciated, drift chamber **28** may not be necessary if pulsed electrons travel through sufficiently long distance, e.g. in a number of optical components (not all shown), before reaching projective lens **12** so that there is a sufficient separation in arrival time at projective lens **12**.

[0049] To illustrate, the results of an example calculation is described below for the following conditions: the initial energies of the pulsed electrons are from 0

to 5 eV, object **16** is biased to –100 V, objective lens **26** and projective lens **12** are grounded, drift chamber **28** is biased to -75 V, the distance between object **16** and projective lens **12** is 12 cm.

[0050] Calculations show that the spread in electron arrival time at lens **12** is approximately 6.28 ns. Recalling equation (2), the potential at projector lens **12**, or, the voltage on the electrodes of lens **12** (or **12'**), need to increase by 5 V within 6.28 ns in order to minimize energy spread at projector lens **12** (or **12'**). Many available fast signal generators can be used for generating this kind of voltage change.

[0051] Since the arrival time at lens **12** (or **12'**) is not linearly dependent on kinetic energy (rather it is linearly dependent on velocity) and since the kinetic energy of an emitted electron varies during its flight to lens **12** (or **12'**), the required change in potential at lens **12** (or **12'**) for obtaining minimum spread in kinetic energy is not linear with time, as shown in **FIG. 3**, where the dotted line shows the linear change in time and the solid lines shows the required change in time.

[0052] The focused pulsed electrons leaving projector lens **12** are detected by detector **34** for forming an image of object **16**. Detector **34** may have a relatively fast response time, e.g., in the sub-nanosecond range, so that the arrival time of pulsed electrons can be recorded accurately. Coarse focusing can be achieved by moving detector **34** along optical axis **20.** Fine focusing can be achieved through varying the magnitude of electrical potential at projector lens **12.**

[0053] Conveniently, as electrons in the emitted beam have been accelerated differently before reaching lens **12** (or **12'**) depending on their initial kinetic energies, the kinetic energies of electrons reaching lens **12** are more uniform, resulting in reduced chromatic aberration.

[0054] Calculations show that EEM **10** can have image resolution in the nano-meter range, more than an order of magnitude improvement over the image

resolution attainable by conventional PEEM systems.

[0055] By dynamically varying the potential on electrode **14**, the energy spread at lens **12** or **12'** is significantly reduced, this means that electrons with differing initial energies are focussed on to approximately the same image plane, significantly reducing the effect of chromatic aberration of the whole system.

[0056] Advantageously, the degree of contrast as compared to conventional X-ray absorption can be enhanced using EEM **10**, since the entire spectrum of the photoelectron signal (from zero to several hundred electron-volts) can be directly monitored. In conventional PEEM systems, only the first few electron volts of the photoelectron energy spectrum is usually used to form the image.

[0057] As should now be appreciated, it is possible to minimize the spread in kinetic energy in different ways. Particularly, the potential at lens **12** or **12'** may be controlled in different ways. For example, an electrically biased tube or plate, remote from lens **12** (or **12'**) and along the path of the pulsed electrons, either at, or upstream or downstream from, lens **12** (or **12'**) may also be used to dynamically vary the focal strength of lens **12** (or **12'**), thus keeping the focal plane constant at the image plane. Similarly, in some situations it may be possible to dynamically modulate the potential at the final projector lens by changing a voltage on detector **34**. Conveniently, modulating the potential of an electrode at or close to lens **12** can be advantageous for reasons such as compactness and ease of use.

[0058] In alternative embodiments, the bias voltage on drift chamber **28** can also be varied in order to examine a particular part of the emission spectrum in more detail. For instance, to examine the energy spectrum at around 200 eV, the drift chamber voltage can be biased to around 200 volts lower than that of the object **16**. This means that all electrons having initial energies below 200 eV would be filtered (not entering drift chamber **28**), while those having energies just above 200 eV will travel slowly through drift chamber **28** and have substantial spread in transit time. Therefore, their energy spectra can be analysed in more

detail by a time of flight spectrometer. In addition, EEM **10** can be used to energy filter emitted photoelectrons from object **16** by selectively detecting them in time at the image plane. The detection system can operate by capturing information within a small time window that can be preset to any point in the detection cycle. Since in the time of flight spectrometer, the detection time directly corresponds to the initial energy of the electrons, time-windowing therefore effectively energy filters the captured image.

[0059] As can be understood, EEMs **10** or **10'** may have alternative and additional components for proper or desired operation, which are readily appreciated and understood by those skilled in the art. For instance, alternative objective or projector lenses may be used. One or more projector lenses may also be added between objective lens **26** and drift chamber **28**, between drift chamber **28** and projector lens **12**, or downstream of projector lens **26**. [Further, where multiple lenses are used, the potentials at more than one lens may be dynamically controlled to reduce the overall chromatic aberration effect. Certain components of EEM **10** or **10'** may also be removed. For instance, in an imaging apparatus similar to EEM **10** or **10'** detector **34** may be removed and the focused emitted electrons may be bombarded on to a target so as to engrave an image of object **16** on the target.

[0060] Other features, benefits and advantages of the present invention not expressly mentioned above can be understood from this description and the accompanying drawings by those skilled in the art.

[0061] Although only a few exemplary embodiments of this invention have been described above, those skilled in the art will readily appreciate that many modifications are possible. The invention, rather, is intended to encompass all such modification within its scope, as defined by the claims.